FIBER AMPLIFIER HAVING MODIFIED GAIN SPECTRUM

BACKGROUND OF THE INVENTION

The present invention relates to fiber amplifiers having means for selectively attenuating or removing unwanted wavelengths to modify or control the amplifier gain spectrum.

Doped optical fiber amplifiers consist of an optical fiber the core of which contains a dopant such as rare earth ions. Such an amplifier receives an optical signal of wavelength λ_s and a pump signal of wavelength λ_p which are combined by means such as one or more couplers located at one or both ends of the amplifier. The spectral gain of a fiber amplifier is not uniform through the entire emission band.

The ability to modify the gain spectrum of a fiber amplifier is useful. Three modifications are of interest: (1) gain flattening, (2) changing the gain slope, and (3) gain narrowing. Gain flattening is of interest for such applications as wavelength division multiplexing. A change in the gain slope can be used to reduce harmonic distortion in AM modulated optical systems (see A. Lidgard et al. "Generation and Cancellation of Second-Order Harmonic Distortion in Analog Optical Systems by Interferometric FM-AM Conversion" IEEE Phot. Tech. Lett., vol. 2, 1990, pp. 519–521) Gain narrowing is of interest because although the amplifier can be operated at wavelengths away from the peak gain without gain narrowing, disadvantages occur due to: increased spontaneous-spontaneous beat noise, a reduction in gain at the signal wavelength because of amplified spontaneous emission at a second wavelength (such as at 1050 nm in a Nd fiber amplifier designed to amplify at 1300 nm), and possible laser action at the peak gain wavelength.

Various techniques have been used for flattening the gain spectrum. An optical notch filter having a Lorentzian spectrum can be placed at the output of the erbium doped gain fiber to attenuate the narrow peak. A smooth gain spectrum can be obtained, but with no increase in gain at longer wavelengths.

Another filter arrangement is disclosed in the publication, M. Tachibana et al. "Gain-Shaped Erbium-Doped Fibre Amplifier (EDFA) with Broad Spectral Bandwidth", Topical Meeting on Amplifiers and Their Applications, Optical Society of America, 1990 Technical Digest Series, Vol. 13, Aug. 6–8, 1990, pp. 44–47. An optical notch filter is incorporated in the middle of the amplifier by sandwiching a short length of amplifier fiber between a mechanical grating and a flat plate. This induces a resonant coupling at a particular wavelength between core mode and cladding leaky modes which are subsequently lost. Both the center wavelength and the strength of the filter can be tuned. The overall gain spectrum and saturation characteristics are modified to be nearly uniform over the entire 1530–1560 nm band. By incorporating the optical filter in the middle of the erbium doped fiber amplifier, the amplifier efficiency is improved for longer signal wavelengths.

SUMMARY OF THE INVENTION

An object of the present invention is t further improve the efficiency of a fiber amplifier and/or tailor the spectral output of a fiber amplifier.

The present invention relates to a fiber amplifier having spectral gain altering means. Fiber amplifiers con-

ventionally comprise a gain optical fiber having a single-mode core containing gain ions capable of producing stimulated emission of light within a predetermined band of wavelengths including a wavelength λ_s when pumped with light of wavelength λ_p. Means are provided for introducing a signal of wavelength λ_s and pump light of wavelength λ_p into the gain fiber. In accordance with this invention, the fiber amplifier is provided with absorbing ion filtering means for attenuating light at at least some of the wavelengths within the predetermined band of wavelengths including the wavelength λ_s.

In accordance with a first aspect of the invention, the absorbing ion filtering means comprises unpumped gain ions; this embodiment requires means for preventing the excitation of the unpumped gain ions by light of wavelength λ_p. In accordance with a further aspect of the invention, the absorbing ions are different from the rare earth gain ions of gain fiber.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic illustration of a fiber amplifier in accordance with the present invention.

FIG. 2 is a graph showing the gain spectra of an erbium-aluminum-doped germania silicate fiber amplifier.

FIG. 3 is a schematic illustration showing a first aspect of the invention.

FIG. 4 is a schematic illustration of an embodiment wherein pump light attenuating means is in series with the gain fiber;

FIG. 5 is a graph illustrating the spectral transmission characteristic of an unpumped erbium-aluminum-doped germania silicate fiber that can be employed in the embodiment of FIG. 4.

FIGS. 6 and 7 are graphs showing gain spectra and spectral transmission for a further mode of operation of FIG. 4.

FIG. 8 illustrates a fiber amplifier in which the pump light attenuating means is an optical fiber;

FIG. 9 is a schematic illustration of a reverse pumped fiber amplifier.

FIG. 10 is a schematic illustration of a dual ended device.

FIGS. 11, 12, and 13 and schematic illustrations of fiber amplifier embodiment in which the gain ion-doped signal filtering means is in series with the gain fiber.

FIG. 14 is a schematic illustration of a fiber amplifier embodiment in which the gain ion-doped signal filtering means is distributed along the gain filter.

FIG. 15 is a graph illustrating the radial distribution of signal and pump power within the gain fiber of FIG. 14.

FIG. 16 is a schematic illustration of a fiber amplifier embodiment in which the gain ion-doped signal filtering means is contained within a fiber that extends along the gain fiber.

FIG. 17 is a graph illustrating the radial distribution of signal and pump power within coupler 83 f FIG. 16.

FIGS. 18 and 19 are schematic illustrations of fiber amplifier embodiment in which the absorbing ions of the signal filtering means are different from the gain ions.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fiber amplifiers typically include a gain fiber 10 (FIG. 1), the core of which is doped with gain ions that are capable of producing stimulated emission of light within a predetermined band of wavelengths including a wavelength λ_s when pumped with light of wavelength λ_p that is outside the predetermined band. A wavelength division multiplexer (WDM) fiber optic coupler 11 can be used for coupling pump energy of wavelength λ_p from laser diode 15 and the signal of wavelength λ_s from input telecommunication fiber 14 to gain fiber 10. Such devices are disclosed in U.S. Pat. Nos. 4,938,556, 4,941,726, 4,955,025 and 4,959,837. Fusion spheres are represented by large dots in the drawings. Input fiber 14 is spliced to coupler fiber 13, and gain fiber 10 is spliced to coupler fiber 12. Splice losses are minimized when coupler 11 is formed in accordance with the teachings of copending U.S. Patent Application Ser. No. 671,075 filed Mar. 18, 1991.

Various fiber fabrication techniques have been employed in the formation of rare earth-doped amplifying and absorbing optical fibers. A preferred process, which is described in copending U.S. Patent Application Ser. No. 07/715,348 filed June 14, 1991, is a modification of a process for forming standard telecommunication fiber preforms. In accordance with the teachings of that patent application, a porous core preform is immersed in a solution of a salt of the dopant dissolved in an organic solvent having no OH groups. The solvent is removed, and the porous glass preform is heat treated to consolidate it into a non-porous glassy body containing the dopant. The glassy body is provided with cladding glass to form a draw preform or blank that is drawn into an optical fiber. The process can be tailored so that it results in the formation of a fiber having the desired MFD. The porous core preform could consist soley of core glass, or it could consist of core glass to which some cladding glass has been added. By core glass is meant a relatively high refractive index glass, e.g. germania silicate glass, that will form the core of the resultant optical fiber.

If the rare earth ions are to extend to a region of the resultant fiber beyond the core, then the porous core preform that is immersed in dopant containing solvent must contain a central core glass region and a sufficiently thick layer of cladding glass. After the resultant doped, cladding-covered core preform has been consolidated, it is provided with additional cladding glass and drawn into a fiber.

If too much rare earth dopant is added to a GeO_2-doped silica core, the core can crystallize. Such higher rare earth dopant levels can be achieved without crystallization of the core glass by adding Al_2O_3 to the core.

As indicated above, it is sometimes desirable to modify the gain spectrum of a fiber amplifier. Since the erbium-doped fiber amplifier has utility in communication systems operating at 1550 nm, that fiber amplifier is specifically discussed herein by way of example. The invention also applies to fiber amplifiers containing gain ions other than erbium, since the gain spectrum of such other fiber amplifiers can also be advantageously modified. As shown by curve 23 of FIG. 2, the gain spectra of an erbium-aluminum-doped germania silicate fiber amplifier has peak around 1532 nm and a broad band with reduced gain to about 1560 nm. It is sometimes desirable to reduce the 1532 nm peak t prevent the

occurrence of such disadvantageous operation as wavelength dependent gain or gain (with concomitant noise) at unwanted wavelengths. Alternatively, it may be desirable t provide the fiber amplifier gain spectrum with a plurality f peaks so the amplifier can operate at a plurality of discrete wavelengths.

In accordance with the present invention, the amplifier spectral gain curve is altered by providing the fiber amplifier with filtering means 17 which includes absorbing ions that modify the gain spectrum by attenuating the amplified signal at various wavelengths in the gain spectrum. In accordance with a first aspect of the invention the absorbing ions are the same rare earth "gain ions" as the active gain ions in gain fiber 10; however, these absorbing gain ions must remain unpumped by light at wavelength λ_p. Such unpumped "gain ions" can be located in a fiber that is in series with gain fiber 10, or they can be distributed along the pumped gain fiber ions of gain fiber 10 but be located at a radius that is sufficiently greater than that of the pumped gain ions that they are substantially unpumped and yet influence the propagation of light of wavelength λ_p. This first aspect is further discussed in conjunction with FIGS. 2 through 17.

In accordance with a further aspect of the invention, the absorbing ions are different from the rare earth gain ions of gain fiber 10; such absorbing ions remain unexcited when subjected to light at wavelength λ_p. The absorbing ions can be positioned as follows: (a) they can be used to co-dope the gain fiber such that they are distributed along with the gain ions (optionally at the same radius as the gain ions), or (b) they can be incorporated into the core of a fiber that is connected in series with gain fiber 10. This further aspect is further discussed in conjunction with FIGS. 18 and 19.

In the figures discussed below, elements similar to those of FIG. 1 are represented by primed reference numerals.

FIG. 3 generally illustrates that embodiment wherein the absorbing ions are the same rare earth "gain ions" as the active dopant ions in the gain fiber. The fiber amplifier system includes unpumped gain ion filtering means 27 for altering the amplifier spectral gain curve. The unpumped gain ions can be located in series with the pumped gain fiber ions of gain fiber 10', or they can be distributed along the pumped gain fiber ions as discussed below in conjunction with FIGS. 14 and 15.

FIG. 4 shows that the unpumped gain ion filtering means can be located in series with the pumped gain fiber ions of fiber 10'. In the absence of an input signal at fiber 14', high levels of pump light can emanate from gain fiber 10'. Furthermore, some fiber amplifiers, especially those based on a three level laser system, are pumped at a power level that is sufficiently high that some remnant pump light emanates from the output end of gain fiber 10'. The presence of pump light along with the amplified signal at output end 30 of gain fiber 10' is indicated by the arrow labeled $\lambda_s + \lambda_p$. Means 31 substantially attenuates the remnant pump light, i.e. only an insignificant level of pump light, if any, remains. However, means 31 leaves the signal light at wavelength λ_s substantially unattenuated, i e. it attenuates signal light less than about 0.5 dB. The arrow at the output f means 31 is therefore labelled λ_s. A length 32 f fiber doped with gain ions is spliced to the utput end f attenuating means 31.

If fiber 10' of FIG. 4 has a germania silicate core doped with erbium and aluminum, f r example, fiber 32

can als be doped with erbium or a combination of dopants including erbium. FIG. 5 shows the spectral transmission characteristic of an optical fiber having a germania silicate core doped with aluminum and un-pumped erbium ions. The reduced transmission be- [5] tween about 1525 and 1560 nm is caused by the absorption of light at those wavelengths by erbium ions. The depression in transmission curve 34 at 1532 nm corresponds to the gain peak in curve 23 of FIG. 2. If fibers 10' and 32 of FIG. 4 are both co-doped with aluminum [10] and erbium ions, the effect of absorbing fiber 32 will be to flatten the spectral gain curve of the resultant fiber amplifier (see curve 24 of FIG. 2).

If gain ion-doped fiber 32 of FIG. 4 had a germania silicate core doped with unpumped erbium ions, its [15] absorption spectra would be represented by curve 35 of FIG. 6. If fiber 10' had the previously described core whereby its gain spectra was represented by curve 23 of FIG. 2, the net gain spectra of the resultant fiber amplifier would be that of FIG. 7. Such an amplifier can [20] operate at three discrete wavelengths along curve 36 where peaks a, b and c are located.

The performance of the gain-ion doped filtering fiber may be improved by quenching the Er fluorescence to minimize signal induced bleaching of the absorption. [25] The Er fluorescence can be quenched by adding dop-ants such as B or OH to the fiber or by increasing the doping density of Er in the absorbing fiber, for example, to levels above 500 ppm in SiO_2-GeO_2 fibers.

Attenuating means 31 of FIG. 4 could consist of a [30] pump light reflector such as a fiber-type grating reflec-tor of the type disclosed in the publication: K.O. Hill et al. "Photosensitivity in Optical Fiber Waveguides: Application to Reflection Filter Fabrication" Applied Physics Letters, vol. 32, pp. 647-649, (1978). [35]

In the embodiment of FIG. 8, the pump light attenu-ating means is a fiber 38 that is spliced between gain fiber 10' and gain ion-doped fiber 32'. Fiber 38 must sufficiently attenuate light of wavelength λ_p that within a relatively short length, e.g. less than 20 m, the pump [40] power at its output end 39 is attenuated to an insignifi-cant level while signal light at wavelength λ_s is not unduly attenuated. Attenuating fiber 38 must be tailored to the specific gain fiber and pump wavelength. If the gain fiber 10' is an erbium-doped optical fiber that is [45] pumped at a wavelength of 980 nm, fiber 38 can be doped with ytterbium, for example. Table 1 lists dopant candidates for use in pump light-absorbing fibers to be employed in conjunction with gain fibers doped with Er, Nd and Pr. [50]

TABLE 1

Gain Ion	Wavelength		Absorbing Ion or Center
	Signal	Pump	
Er	1.52–1.6 μm	980 nm	Yb, Dy, Pr, V, CdSe
Er	1.52–1.6 μm	1480 nm	Pr, Sm	[55]
Er	1.52–1.6 μm	800 nm	Nd, Dy, Tm, V, CdSe
Nd	1.25–1.35 μm	800 nm	Dy, Er, Tm, V, CdSe
Pr	1.25–1.35 μm	1000 nm	Dy, Er, Yb, V,

Curves of absorptivity v. wavelength were used in se- [60] lecting the rare earth ions and the transition metal (va-nadium) ion. The CdSe should be present in the absorb-ing fiber in the form of micro crystallites.

The light attenuating fiber means of this invention is also useful in fiber amplifiers employing alternate pump- [65] ing schemes. In the counter-pumping device f FIG. 9, wherein elements similar to those of FIG. 8 are repre-sented by primed reference numerals, gain fiber 10' is

connected to input fiber 14' by attenuating fiber 38' and gain ion-doped fiber 32'. Pumping light of wavelength λ_p is coupled to gain fiber 10' by coupler 41 which also couples the amplified signal to output fiber 20'. Attenuating fiber 38' removes pump light that would have excited the gain ions in fiber 32'. Since the gain ions in fiber 32' remain unexcited by pump light, fiber 32' filters the incoming signal.

In the dual-ended device of FIG. 10, coupler 43 couples the signal from input telecommunication fiber 45 and pumping power from first pump source 44 to gain fiber section 46a, as described in conjunction with FIG. 4. Coupler 47 couples pumping power from second pump source 48 to gain fiber section 46b. The output signal of wavelength λ_s is coupled by coupler 47 from gain fiber section 46b to outgoing telecommunication fiber 50. Pump light attenuating fibers 52a and 52b are spliced to gain fiber sections 46a and 46b. A length 53 of fiber doped with gain ions is spliced between attenuating fiber sections 52a and 52b. In the absence of the attenuating fiber sections, remnant pump light from sources 44 and 48 would be coupled from the gain fiber sections 46a and 46b, respectively, to gain ion-doped fiber 53, thereby negating its filtering ability. Since the characteristics of fiber 53 are similar to those of fiber 32' of FIG. 8, the fiber amplifier is provided with a modified spectral gain.

The signal is first introduced into section 46a where it gradually increases in amplitude due to amplification in that section. The amplitude of the original that is introduced into section 46b is therefore much greater that that which was introduced into section 46a. The pump power is therefore absorbed at a greater rate per unit length in section 46b, and section 46b can be shorter than section 46a.

In the embodiment of FIG. 11 the length of gain fiber 57 is sufficient to dissipate all of the pump light from source 15' so that essentially no pump light reaches end 58 thereof. Gain ion-doped fiber 32' can therefore filter the amplified signal. However, for lowest noise amplification, an adequate pump light intensity should exist throughout the amplifier medium. The amplifier of FIG. 11 therefore generates more noise than previously described embodiments.

Gain fiber 62 of FIG. 12 can be provided with pump power from either or both of the couplers 60 and 61. This embodiment pertains to forward pumped, reverse pumped and double pumped fiber amplifiers. In the reverse pumped embodiment, coupler 60 is unnecessary. In all cases, the signal is amplified by gain fiber 62 and coupled to outgoing telecommunication fiber by coupler 61. In the reverse pumping mode, pump light propagates from coupler 61 into end 65 of gain fiber 62. In the forward and double pump situations, only a small fraction of the remnant pump light exiting output end 65 of fiber 62 is coupled to coupler fiber 66. Since gain ion-doped fiber 64 remains essentially unpumped, it filters the amplified signal light that is coupled to outgoing telecommunication fiber 63.

FIG. 13 shows a simplified embodiment wherein filtering fiber 74 contains a dopant that absorbs pump light; it also contains gain ions for altering the amplifier spectral gain curve. The concentration of the pump light attenuating ions is such that their absorption is much greater than that of the gain i ns in fiber 74. For example, the absorption of pump light might be ten times the absorption of signal light. Thus, the remnant

pump light is absorbed within a sh rt distance of the input end 75 of fiber 74. The remainder f fiber 74 filters the amplified signal from fiber 10'.

In the embodiment of FIG. 14, gain fiber 79 itself is designed such that it contains dopant ions at a sufficiently large radius that only the relatively large mode field of the signal light reaches the large radii dopant ions. As shown in FIG. 15, the signal field extends to a greater radius in gain fiber 79 than the pump field. If the signal field extends to radius r_2, the erbium ions, for example, should also extend to a radius of about r_2. Since Er ions having radii larger than about r_1 remain umpumped, those large radii Er ions are available for filtering the signal.

The embodiment of FIG. 16 employs a fiber optic coupler-type device 83 that is formed by fusing together a gain fiber 81 and a gain ion doped signal attenuating fiber 82. Device 83 can be similar to the overclad coupler of the type disclosed in U.S. Pat. No. 4,931,076 or the fused fiber coupler of the type disclosed in T. Bricheno et al. "Stable Low-Loss Single-Mode Couplers" Electronics Letters, vol. 20, pp. 230–232 (1984). Pump light and signal are coupled to gain fiber 81 from input coupler fiber 12'. The fibers 81 and 82 of coupler 83 have sufficiently different propagation constants that, because of the resultant $\Delta\beta$, no coupling occurs. However, the large radius signal field from gain fiber 81 significantly overlaps the absorbing region of fiber 82 in that portion of the coupler where fibers 81 and 82 are fused together and stretched to decrease the distance between cores. Since there is a negligible overlap of the smaller radius pump field into the gain ion-doped region of fiber 82 (see FIG. 17), the gain ions remain unexcited and can filter the signal light.

That aspect of the invention wherein the signal absorbing ions are different from the rare earth gain ions of the gain fiber is illustrated in FIGS. 18 and 19. The fiber amplifier of FIG. 18 includes gain fiber 90, the core of which is doped with gain ions that are capable of producing stimulated emission of light within a band of wavelengths including a wavelength λ_s when pumped with light of wavelength λ_p. The signal and pump light are coupled to gain fiber 90 via coupler fiber 12'. Gain fiber 90 is co-doped with absorbing ions that are different from the gain ions; therefore, the pump light attenuating means of the previous embodiments can be eliminated. Table 2 lists dopant candidates for use as absorbing ions to be employed in conjunction with gain fibers in which Er, Nd and Pr are the gain ions.

TABLE 2

Gain Ion	Gain Wavelength Range	Absorbing Ion
Er	1.52–1.61 μm	Pr, Sm
Nd	1.25–1.35 μm (undesired gain at 1090 nm)	Sm, Dy, Pr
Pr	1.25–1.35 μm	Sm, Dy, Nd

Curves of absorptivity v. wavelength were used in selecting the absorbing ions of Table 2.

During the fabrication of a preform for drawing a gain fiber that is co-doped with absorbing ions as well as active gain ions, the central region of the fiber is provided with a sufficient concentration of active gain ions to provide the desired amplification; it is also provided with a sufficient concentration of absorbing ions to attenuate the undesired portion or modify the gain spectrum. Such a fiber could be formed in accordance with

the aforementioned U.S. Pat. Application Ser. No. 07/715,348 by immersing the porous core preform in a dopant solution containing salts of both the active dopant ion and the absorbing i n.

5   That embodiment wherein the absorbing ions are incorporated into the core of a fiber that is connected in series with gain fiber is shown in FIG. 19 wherein absorbing fiber 93 is spliced between two sections 92a and 92b of gain fiber. Alternatively, the absorbing fiber

10   could be spliced to the output end or input end of a single section of gain fiber.